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Climate change, land use change, and China's food security in the twenty-first century: an integrated perspective

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Abstract Food security in China, the world's most populous country, has long been a concern because of the challenges of population growth, water shortages, and loss of cropland through urbanization, soil degradation, and climate change. Here, we present an integrated analysis of China's food demand and supply under IPCC Special Report on Emissions Scenarios A1, A2, B1, and B2 in 2020, 2050, and 2080, based on official statistics and future development scenarios. Our analysis accounts for future socioeconomic, technological, and resource developments, as well the impact of climate change. We present a covariant relationship between changes in cereal productivity due to climate change and the cereal harvest area required to satisfy China's food demand. We also estimated the effects of changing harvested areas on the productivity required to satisfy the food demand; of productivity changes due to climate change on the harvest area required to satisfy food demand; and of productivity and land use changes on the population at risk of undernutrition. China could be able to feed herself without disturbing the global food market in the twenty-first century, but whether the government will choose self-sufficiency or increased food imports may depend on the cost of change, which remains unknown.

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1 Introduction

Despite impressive success in increasing the food supply to meet the demands of rapidly growing populations during the past few decades, concerns over the ability of developing countries to sustain their people and over possible impacts on the global food market have not decreased. For example, on the basis of projections to 2020, the International Food Policy Research Institute has expressed serious concerns about whether the world food production system will be able to feed the projected population, especially in the face of a possibly stagnant or even declining stock of natural resources (Rosegrant et al. 2001). The World Research Institute has stated that the challenge of meeting human needs seems destined to grow ever more difficult (WRI 2000). This issue also concerns the UN Food and Agricultural Organization (FAO). According to their projections, the increase in crop production in developing countries from 1995–1997 to 2030 will be only 70%, versus 175% over the preceding 34-year period (FAO 2001). The impact of global changes in food security is becoming a serious concern (e.g., Parry et al. 2004; Easterling et al. 2007). Because of climate change, regional differences in crop production are likely to grow stronger over time, leading to increased regional disparities, with substantial increases in the risk of hunger among poorer nations, especially under scenarios of greater inequality (Parry et al. 2004).

Food security in China, one of the largest and most populous countries in the world, has been a major concern since at least the 1990s (e.g., Brown 1995; Heilig 1999; Tao et al. 2003, 2008; CHINAGRO 2005; Lin et al. 2005; Xiong et al. 2007). Because of the challenges caused by population growth, water shortages (Tao et al. 2003), loss of cropland due to urbanization (Liu et al. 2005a, b), soil degradation (Tao et al. 2005), and climate change (Tao et al. 2006), the need for reliable predictions of food production and potential adaptation options has become increasingly important. Future food demand and supply are strongly related to the country's future population, economy, technology, resources, climate, and other factors. Current studies have generally failed to comprehensively account for changes and adaptations in future land-use, socioeconomic and technological scenarios. More integrated multidisciplinary studies are needed to provide reasonable scenarios for future changes. However, since the problem of predicting future food production is becoming more and more complex, the time is not yet ripe for designing a comprehensive coupled model that accounts for all the factors that will have a significant influence on food production (Döös 2002). Nevertheless, recent advances in scenario development make it possible to perform a reasonably well-integrated analysis. For example, on the basis of an analysis of a range of development and policy scenarios over a 30-year time horizon, CHINAGRO (2005) tried to establish an informed policy dialogue between China and the European Union to improve food security, farmer income, and sustainable agricultural development in China. Ewert et al. (2005) and Rounsevell et al. (2005) predicted changes in crop productivity and agricultural land use in Europe by using scenarios that represent alternative economic and environmental pathways for future development.

Here, we account for the major factors in an integrated perspective on future food demand and supply in China under Intergovernmental Panel on Climate Change (IPCC) Special Report on Emissions Scenarios (SRES) A1 (a global economic world), A2 (a regional economic world), B1 (a global environmental world), and B2 (a regional environmental world) (Nakićenović and Swart 2000) in 2020, 2050, and 2080. The aims of this paper are: (1) to estimate the effects of changes in harvested area on the productivity change required to satisfy the demand for food; (2) to estimate the effects of changes in productivity due to climate change on the harvested area required to satisfy food demand; and (3) to estimate the effects of productivity and land use change on the nutritional status of China's population.

2 General description of the model

The model we developed is based on a supply–demand equilibrium ($S = D$). In this analysis, the food supply includes both domestic food production and imports. We assume that the net import of cereals will be kept to within 5% of future food demand owing to China's goal of increasing its food self-sufficiency (Alexandratos 1999). The supply from domestic food production is calculated on the basis of the available land area (L) and productivity (P) and a term that accounts for under-supply (U, relative to the satisfactory supply) at a given time in the future (t) compared with the present baseline (t_0). Because of the equilibrium assumption, besides the import demand (D) is then equated to this production:

$$\frac{D_t}{D_{t_0}} = \frac{L_t}{L_{t_0}} \frac{P_t}{P_{t_0}} \frac{U_{t_0}}{U_t} \tag{1}$$

In the model, demand is calculated from the gross domestic product (GDP) and population. Productivity is calculated considering effects of climate change, increases in the atmospheric CO_2 concentration, and technological development. Land use is calculated as the ratio of harvested area (here, for cereals) to the total cropland area. Under-supply represents the total population at risk of undernutrition. GDP, population, CO_2 increase, technological development, and land use all change depending on the assumptions of each SRES scenario.

The future change in cereal productivity is assumed to depend on technological development, the CO_2 fertilization effect, and the impacts of climate change (excluding any CO_2 fertilization effect). We use the equations developed by Ewert et al. (2005) to calculate changes in future (t) productivity (P) relative to the present baseline (t_0), as affected by climate change, increasing CO_2 concentration, and technological development, respectively:

$$\frac{P_{t_0}}{P_t} = \frac{1}{1 + \left[\left(P_{t,\mathrm{Cl}} \middle/ P_{t_0} - 1\right) + \left(P_{t,\mathrm{CO_2}} \middle/ P_{t_0} - 1\right) + \left(P_{t,T} / P_{t_0} - 1\right)\right]}, \tag{2}$$

where $P_{t,\mathrm{Cl}}$, $P_{t,\mathrm{CO_2}}$, and $P_{t,T}$ represent future productivity as affected by climate change, increasing CO_2 concentration, and technological development, respectively. The effect of technological development on crop yield was estimated as:

$$\frac{P_{t,T}}{P_{t_0}} = Y_r\left(t_0\right) + \int_{t_0}^{t=t_\mathrm{s}} \left(\frac{Y_{r,\mathrm{a}} \cdot f_{T,P_r(t)} \cdot f_{T,G_r(t)}}{Y_{\mathrm{gp}}\left(t_0\right)}\right) \mathrm{d}t, \tag{3}$$

where $Y_r(t_0)$ is the relative yield change at t_0, and t_s is the scenario time period. $Y_{r,a}$ represents the annual increment in the relative yield change with respect to the baseline year t_0 and is calculated from $[Y_r(t_0) - 1]$. Historical gains in potential yield were set to 1 and $f_{T,P_r(t)}$ accounts for any future diversion from this gain. $Y_{gp}(t_0)$ represents the ratio of actual crop yields to potential yields at t_0 and $f_{T,G_r(t)}$ represents the ratio of actual yield to potential yield in the future.

The effect of increasing CO_2 on crop yield was calculated from:

$$\frac{P_{t,CO_2}}{P_{t_0}} = \frac{f_{CO_2,r} \cdot \Delta C_{t-t_0}}{100} + 1, \tag{4}$$

where $f_{CO_2,r}$ is the relative yield change per unit increase in CO_2 and ΔC_{t-t_0} is the difference between future and present CO_2 concentrations. Increases in atmospheric CO_2 concentrations for the different IPCC SRES scenarios and time slices were projected by IMAGE-team (2001).

Our analysis focuses on estimating the:

- Effects of changes in harvested area on the productivity changes required to satisfy the demand for food. This is obtained from Eq. 1 by rearranging it to solve for P, with L subject to change and D held constant.
- Effects of changes in productivity due to climate change on the harvested area required to satisfy food demand. This is obtained from Eq. 1 by rearranging it to solve for L, with P subject to change (as a result of climate change) and D held constant.
- Effects of productivity and land use change on under-supply (undernutrition). This is obtained from Eq. 1 by solving it for U, with L subject to change, and P and D held constant.

3 Estimation of model parameters

3.1 Projected development in food demand in the twenty-first century

3.1.1 Relationship between per capita annual food demand and GDP

There is a robust relationship between per capita annual food demand and per capita GDP based on data from 1961 to 2003 (Fig. 1). The population and GDP data were obtained from the *China Statistical Yearbook*, published by China Statistics Press (Beijing). The GDP was converted into 1990 US$ by using the 1990 market exchange rate to match the unit of projected GDP for future (Gaffin et al. 2004) Annual food demand for the period was calculated from domestic consumption of cereals and meat, on the basis of the statistical databases of FAO (FAO 2004). Consumption of cereals includes rice, wheat, maize, and other grains used directly as food, as seed, in the manufacture of processed foods, and for other related uses. The consumption of meat (mainly pork, poultry, and beef) was converted into a cereal equivalent by using conversion factors (7.0 kg grain/kg beef, 4 kg grain/kg pork, 2 kg grain/kg poultry) provided by the Food Climate Research Network (http://www.fcrn.org.uk). Annual per capita food demand was then calculated by dividing the annual food demand by the population.

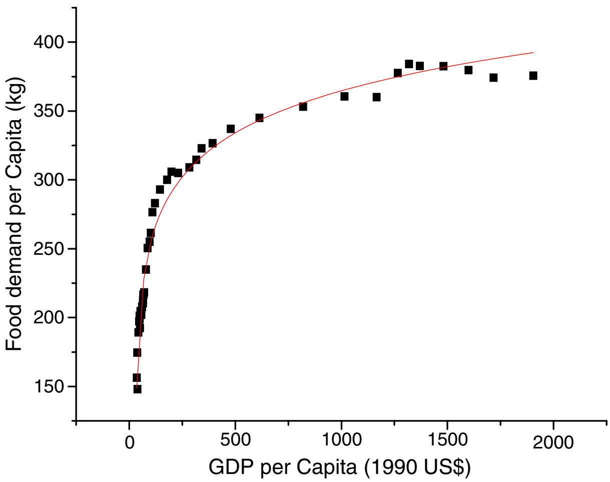

Fig. 1 Regression relationship between per capita annual food demand and per capita GDP (in 1990 US$). The regression equation is: $y = 74.72 + 42.16\ln(x - 30.37)$, $r^2 = 0.98$, $n = 43$

3.1.2 Projected development in food demand in the twenty-first century

We estimated China's future population and GDP for IPCC scenarios A1, A2, B1, and B2 on the basis of the values of these parameters in 2000 (National Bureau of Statistics of China 2005) and projected growth rates. The latter were calculated from downscaled socioeconomic scenarios for future population and GDP at the country level (Gaffin et al. 2004), as based on the recent IPCC SRES (Nakićenović and Swart 2000). The scenarios cover a wide range of future changes in population and GDP (Fig. 2). The A2 scenario projects the greatest increase in population. In contrast, population is projected to decrease after a peak at around 2020 under the A1 and B1 scenarios and to stabilize under the B2 scenario. GDP is projected to increase most under the A1 scenario.

We applied the robust relationship between per capita annual food demand and GDP, together with the projected population and GDP scenarios to project future food demand. The projected per capita annual food demand depended on the scenario, with the highest value under scenario A1 and the smallest value under scenario A2 (Table 1). It ranges from 412.1 to 449.6 kg cereal grain per year in 2020, from 445.4 to 524.2 kg cereal grain per year in 2050, and from 476.6 to 562.4 kg cereal grain per year in 2080. Together with the projected population, total food demand is projected to increase most under scenario A2 owing to its projected sharp increase in population. In contrast, under scenarios A2 and B1, total food demand is projected to decrease after peaking in around 2040, in response to the projected decrease in population after peaking in around 2020 (Fig. 3).

3.2 Future cereal productivity

We used China's historical cereal yield data and the method of Ewert et al. (2005) to estimate changes in cereal productivity due to technological advances and the CO_2 fertilization effect, respectively. China's historical cereal yield data were obtained from the FAO (2004) statistical databases. The relative yield change at the base year (i.e., the ratio of yield in 2000 to yield in 1999) was set to 1.019. We assumed

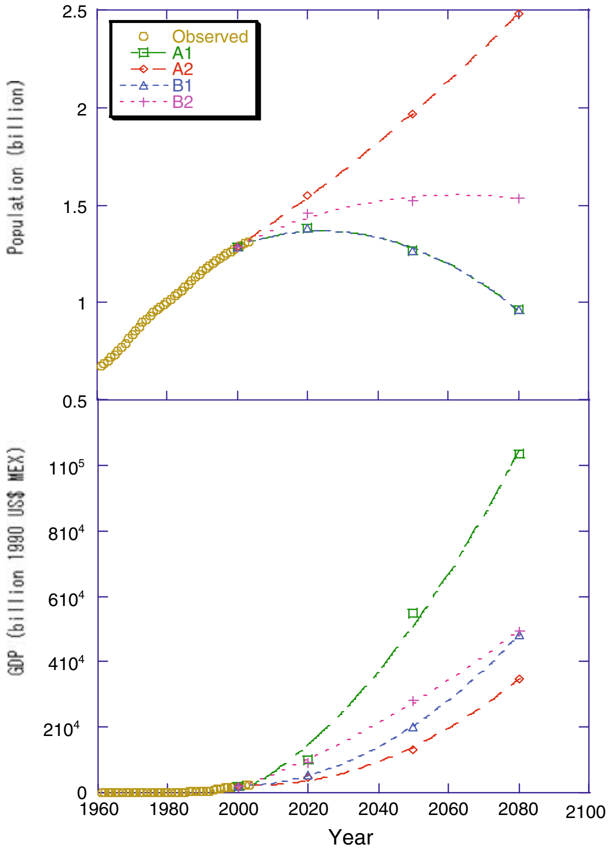

Fig. 2 Future population and GDP in China as projected for IPCC scenarios A1, A2, B1, and B2

that the present actual crop yields are about 75% of the potential yields. From these assumptions, the changes in cereal productivity due to technological advances and the CO_2 fertilization effect are shown in Fig. 4. The relative yield change per unit increase in CO_2 concentration was set to 0.08% ppm^{-1}, suggesting that doubling the present CO_2 concentration would increase crop yield by about 30% (Ewert et al. 1999). Cereal productivity is projected to increase most in response to CO_2 fertilization and technological development under the A1FI scenario as a result of relatively high atmospheric CO_2 concentrations and rapid technological development. In contrast, the contribution of technological development to cereal productivity is projected to decrease from 2050 to 2080 under scenarios B2 and B1.

Table 1 Projected per capita annual food demand (in kg cereal grain) in China for IPCC scenarios A1, A2, B1, and B2

Year	A1	A2	B1	B2
2000	381.5	381.5	381.5	381.5
2020	449.6	412.1	423.0	443.5
2050	524.2	445.4	482.0	488.3
2080	562.4	476.6	530.3	511.7

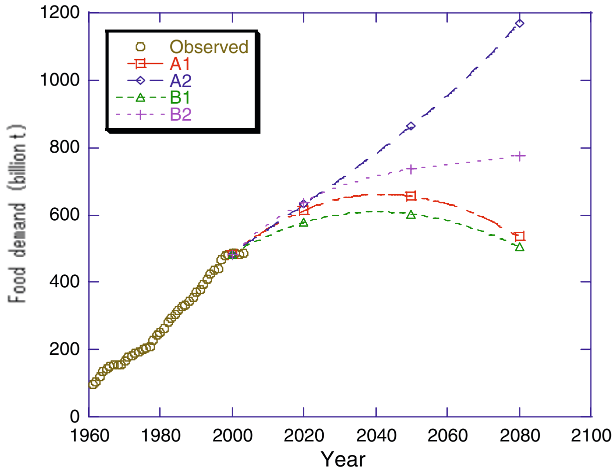

Fig. 3 Observed and projected food demand in China for IPCC scenarios A1, A2, B1, and B2

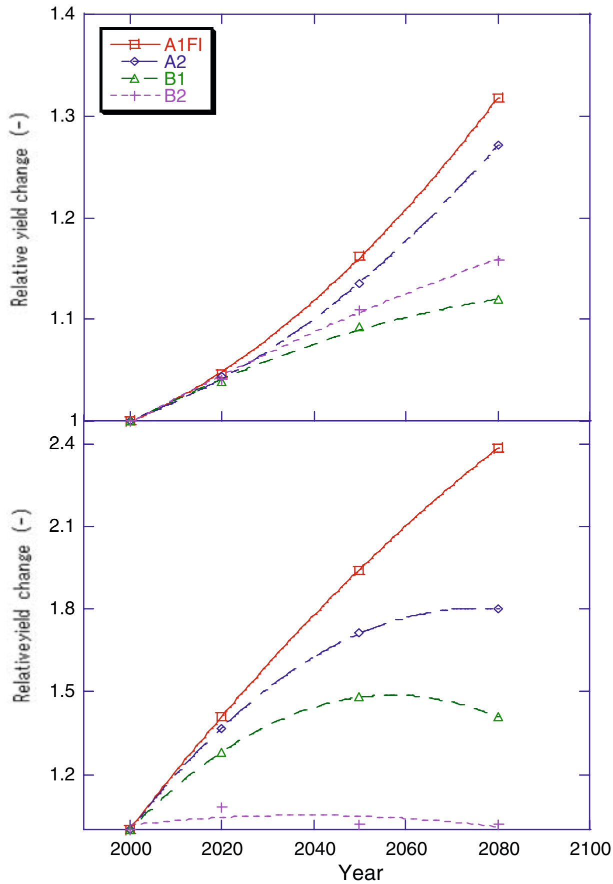

Fig. 4 Projected cereal productivity change due to CO_2 fertilization effects (*upper*) and technology development (*down*) for IPCC scenarios A1, A2, B1, and B2

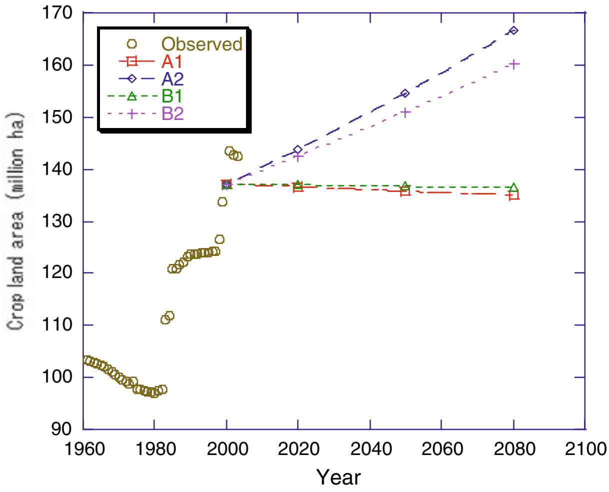

Fig. 5 Observed and projected total cropland area in China for IPCC scenarios A1, A2, B1, and B2

3.3 Future cropland resources

The future cereal harvest area will depend on the total future cropland area and the ratio of cereal harvest area to the total cropland area (i.e., *H*/*C*). *H*/*C* could be higher than 100% because harvest area could be larger than cropland area in the region with double or triple cropping system which allows multiple harvests per year. We assumed that China's cropland area would have the same growth rates as the whole Asia under all four scenarios, as was predicted by the Asian Pacific Integrated Model (Morita et al. 1994). The cropland areas in China from 1961 to 2003 were obtained from the statistical databases of FAO (2004). We then estimated China's future cropland area by increasing the 2000 value by its annual growth rate. Cropland area would increase linearly under scenarios A2 and B2, but would decrease linearly under scenarios A1 and B1 (Fig. 5).

4 Projected impacts of changes in climate and land use on food security

4.1 Effects of changes in harvested area on the productivity change required to satisfy the demand for food

We define food security as meaning that China can meet the food demand for all of her population (using 95% domestic production and 5% imports) according to a living standard based on per capita GDP in the projected year. With the H/C ratio increasing from 20% to 100%, to satisfy the increasing demand for food, the required change in cereal productivity due to climate change (excluding the CO_2 fertilization effect) in the four scenarios would range from −56% to 335% in 2020, from −114% to 374% in 2050, and from −191% to 494% in 2080 on the basis of China's cereal yield (i.e., 4,756.4 kg/ha) in 2000 (Fig. 6). This means that if *H*/*C* were 100%, cereal productivity could decrease by up to 56%, 114%, and 191% in 2020, 2050, and 2080, respectively as a result of climate change, compared with the productivity in 2000,

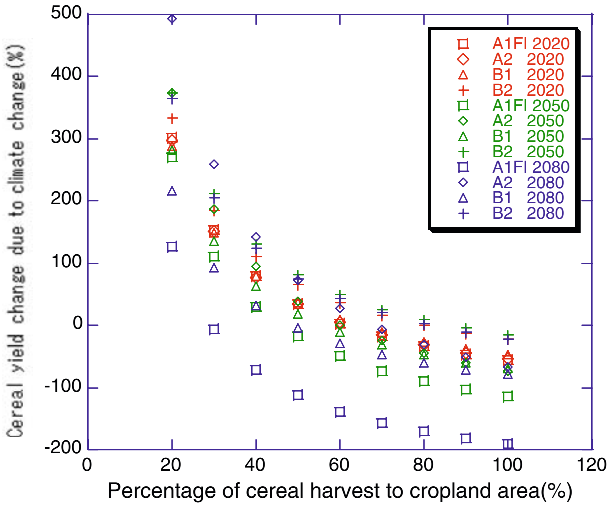

Fig. 6 The covariant relationship between cereal yield change due to climate change and H/C to satisfy food demand in 2020, 2050, and 2080

without failing to meet food demand. However, if H/C were only 20%, satisfying the demand for food would require cereal productivity to increase by no less than 335%, 374%, and 494% in 2020, 2050, and 2080, respectively, compared with the productivity in 2000.

4.2 Effects of changes in productivity due to climate change on the harvested area required to satisfy food demand

Previous estimates (Parry et al. 2004) showed that climate change (excluding the CO_2 fertilization effect) would decrease cereal yield in China by 2.5% to 5%, 2.5% to 10%, 0% to 2.5%, and 2.5% to 5% in 2020 under scenarios A1FI, A2, B1, and B2, respectively, compared with the 1990 value, versus corresponding decreases of 5% to 10%, 5% to 10%, 5% to 10%, and 5% to 10% in 2050, and 10% to 30%, 5% to 30%, 5% to 10%, and 5% to 10% in 2080. If so, satisfying food demand under scenarios A1FI, A2, B1, and B2 would require an H/C value of at least 61% to 62%, 61% to 65%, 62% to 63%, and 79% to 81%, respectively, in 2020, versus values of 46% to 47%, 60% to 62%, 56% to 58%, and 88% to 92% in 2050 and 30% to 32%, 67% to 77%, 49% to 50%, and 83% to 87% in 2080 (Fig. 6).

4.3 Effects of productivity and land use change on undernutrition

Using the mean impact of climate change proposed by Parry et al. (2004) for further estimation, and with H/C changing from 20% to 100%, the number of people at risk of undernutrition would change from 955–1,107 to −708 – −221 million in 2020s, from 750–1,356 to −1, 251 – −44 million in 2050s, and from 381–1, 823 to −1,906 – −125 million in 2080s (Fig. 7). This means that if H/C were 100%, besides satisfying the food demand for all of her population, China could have food surplus. The food surplus is equivalent amount of food demand of 221 to 708 million people in 2020s, of 44 to 1,251 million people in 2050s, and of 125 to 1,906 million people in 2080s. However, if H/C were only 20%, the number of people at risk of undernutrition

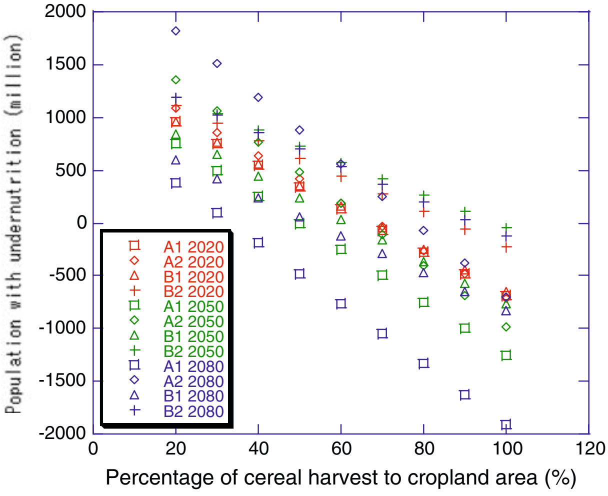

Fig. 7 The changes of population at risk of undernutrition in response to *H*/*C*

would be 955 to 1,107 million in 2020s, 750 to 1,356 million in 2050s, and 381 to 1,823 million in 2080s.

5 Discussion

Our analysis shows that food security is closely related to the proportion of the total cropland used to grow cereals (i.e., *H*/*C*). FAO data suggest that, from 1961 to 2003, China's *H*/*C* value increased linearly from 87% in 1961 to a peak of 101% in 1976, and then decreased sharply to 73% in 1985. After 13 years of stability, it again decreased sharply, from 68% in 1999 to 54% in 2003 (Fig. 8). The changes in

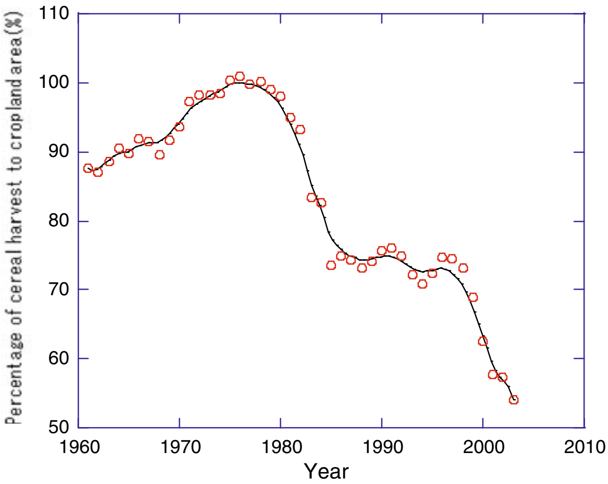

Fig. 8 Annual change in *H*/*C* (%) in China from 1961 to 2003

the area of cereal harvest were influenced mainly by government policy (Tong et al. 2003), market price fluctuations, and climate variability (Tao et al. 2004). Our results suggest that H/C will have to increase to satisfy the food demand of the increasing population. Fortunately, land resource data and historical experience suggest that the cereal harvest area required in the future would not be beyond the capacity of China's land resources and the control of the government. Furthermore, climate change (i.e., an extended growing season) would lead to an increased potential to use multiple cropping systems. Therefore, our results suggest that China will have the capacity to feed itself without disturbing the world food market in the twenty-first century. The key problem with this assertion is, however, whether there is sufficient motivation. Would the government be willing to increase C/H to maintain agricultural self-sufficiency instead of increasing food imports? Would this strategy prove too costly? These questions are worthy of further investigation. Alternatively, improved resource-use efficiency and new technological development should be greatly encouraged to boost agricultural production (Huang et al. 2002). The low incomes of farmers and high agricultural production costs are serious obstacles to achieving this goal.

Our analysis uses a highly integrated framework based on official statistics (e.g., FAO and the *China Statistical Yearbook*) and state-of-the-art future development scenarios (IPCC SRES). Technology, cropland area, and per capita food demand all change dynamically in these scenarios, which are more reasonable than the scenarios used in previous studies. The future scenarios we used for socioeconomic development, technological advances, land use changes, and the impacts of climate change were obtained from integrated modelling. The robustness of our analysis is, therefore, dependent on the reliability of the scenarios. China's population policy should soon lead to zero population growth and a population decline within the modelling period. That supports the assertions in scenario A1, and this will increase food security. In contrast, urbanization, desertification and land degradation, combined with conservation, will greatly reduce the land available for agriculture. That will decrease food security, particularly in a scenario with high population growth and low GDP growth. Nevertheless, the approach illustrated in our paper provides what is currently the most advanced way to imagine the future. The scenarios (including land-use scenarios) cover a wide range of key future characteristics such as population growth, economic development, and technological change. Therefore, our analysis also indirectly included some important issues such as urbanization, and competition for resources. Cereal productivity changes in response to climate change also indirectly reflected the key issue of water resources.

As a country-level analysis, our analysis was not spatially explicit, and it did not account for the enormous spatial and social diversity of China, which is however an important problem (CHINAGRO 2005). In fact, there is high variation throughout China in population density, lifestyles, crop-growing conditions, cropping patterns, and crop yields. In addition, there are large discrepancies among the estimates of cropland area in China (Heilig 1999; Liu et al. 2005a for a review). Estimates of the total cropland area in China in the base year (i.e., 2000) range from 128.3 million ha (Heilig 1999) to 137.1 million ha (FAO 2004) and 141.1 million ha (Liu et al. 2005a). Here, we used the FAO estimate to match the source of our other statistics; although the estimation based on Landsat TM/ETM data by Liu et al. (2005a) may be more accurate. If using the estimates by Liu et al. (2005a), we can adopt a more optimistic view of the food supply; for example, in Fig. 6, the required cereal productivity change due to climate change would be 2% to 4% less, although the general trends and conclusions would remain the same.

6 Conclusions

We have provided an integrated perspective on China's food demand and supply in the twenty-first century based on official statistics and the use of state-of-the-art future scenarios. Our scenarios cover a wide range of key future characteristics, such as population growth, economic development, and technological change; therefore, our analysis presents a reasonably integrated picture of China's future food demand and supply. We conclude that China has the potential to feed itself without disturbing the world food market in the twenty-first century. However, whether the government will choose self-sufficiency or increased food imports may depend on the relative costs of these two alternatives. Given the importance of China's food security, this issue is worthy of further investigation.

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